

# Power Spectrum Analysis of Far-IR Background Fluctuations in 160 $\mu\text{m}$ Maps From the Multiband Imaging Photometer for Spitzer

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**Abstract.** We describe data reduction and analysis of fluctuations in the Cosmic Far-IR Background (CFIB) in large maps observed with the Multiband Imaging Photometer for Spitzer (MIPS) instrument 160  $\mu\text{m}$  detectors. We analyzed the extragalactic First Look Survey (FLS) and the Spitzer Wide-area Infrared Extragalactic Survey (SWIRE) Lockman Hole observations, the latter being the largest low-cirrus mapping observation available. In the Lockman Hole map, we measured the power spectrum of the CFIB by fitting a power law to the IR cirrus component, the dominant foreground contaminant, and subtracting this cirrus signal. The CFIB power spectrum at mid-high  $k$  ( $k \approx 0.2 - 0.5 \text{ arc min}^{-1}$ ) is consistent with previous measurements of a relatively flat component. At lower  $k$ , however, the power spectrum is clearly not flat, decreasing from our lowest frequency ( $k = 0.03 \text{ arc min}^{-1}$ ) and flattening at mid-frequencies ( $k \approx 0.1 - 0.2 \text{ arc min}^{-1}$ ). This behavior is consistent with the gross characteristics of predictions of a source clustering “signature” in CFIB power spectra, and this is the first report of such a detection.

**Key words.** cosmology: diffuse radiation, infrared: general

## 1. Introduction

Spatial fluctuations in the cosmic far-IR background (CFIB) were first discovered with ISO at 170  $\mu\text{m}$  in a relatively small field ( $0.25 \text{ deg}^2$ ; Lagache & Puget 2000). They have also been detected with IRAS data, after re-processing (Miville-Deschenes, Lagache & Puget 2002). The origin of the CFIB is believed to be the ensemble emission from galaxies too faint to be resolved; the spectrum, intensity, and spatial distribution of the CFIB therefore contain information about the distribution of galaxy emission in space and time. Lagache, Dole, and Puget (2003) showed that while a variety of luminosity functions might fit far-IR source counts and total background level, the fluctuations in the CFIB require that the luminosity function must change dramatically with redshift, with a rapid evolution of the high-luminosity sources ( $L > 3 \times 10^{11} L_{\odot}$ ) between  $z = 0$  and 1.

CFIB fluctuations should also yield information on the spatial distribution, i.e. clustering, of IR emitting galaxies. A Gaussian distributed field of sources would yield a flat

CFIB power spectrum. Perrotta et al. (2003), however, have predicted that a large excess would be present in the low- to mid- frequencies of the power spectrum if source clustering is present. Lagache & Puget (2000) states that it was not possible to measure a clustering signal in the data analyzed, primarily because the small field size caused difficulties in fitting and separating the cirrus signal.

The Spitzer Space Telescope MIPS instrument (Rieke et al. 2004) has observed much larger fields than Lagache & Puget (2000) with low IR cirrus emission that are ideal for study of the structure of the CFIB. The longest wavelength array has a nominal bandpass of  $\sim 35 \mu\text{m}$  around its center wavelength of 160  $\mu\text{m}$ , and is the most sensitive instrument to date in this wavelength range. Cirrus and zodiacal emission are weak relative to the unresolved CFIB in this band. At 160  $\mu\text{m}$ , 18% of the CFIB light is predicted to be resolved into sources with MIPS (Dole, Lagache, & Puget 2003) so CFIB emission actually dominates source emission in this band.

In order to take advantage of the capabilities of MIPS for CFIB fluctuation studies at the longest wavelength, we have undertaken a program to reduce and analyze the largest low-

**Table 1.** Map Fields

Field	RA <sup>a</sup>	Dec <sup>a</sup>	Area	Square Area <sup>b</sup>	ISM Background <sup>c</sup> (Predicted)	Total Background (Predicted <sup>c</sup> )	Total Background (Measured <sup>d</sup> )
	(J2000)	(J2000)	(deg <sup>2</sup> )	(deg <sup>2</sup> )	(MJy/Sr)	(MJy/Sr)	(MJy/Sr)
FLS	17:18:00	+59:30:00	4	4.02	2.4	4.4	5.86 <sup>e</sup>
SLH	10:47:00	58:02:00	14.4	8.47	1.1	3.6	4.27 <sup>e</sup>

<sup>a</sup>Position of Field Center,<sup>b</sup>Area of square subsection of map used in our analysis.<sup>c</sup>Mean ISM or total background estimated at 160  $\mu$ m by SPOT for epoch of observation.<sup>d</sup>Median of reduced map.<sup>e</sup>Note that for the version10 BCD data, the measured backgrounds for the FLS and SLH maps were 7.4 and 5.5 MJy/Sr, respectively.

background fields observed by the MIPS instrument. This paper describes the current status of our efforts to construct and analyze these large 160  $\mu$ m Spitzer MIPS maps using power spectrum analysis. The basic characteristics of the map observations that we analyzed are given in Table 1.

## 2. Map Observations and Reduction

### 2.1 Observations

As of this writing, the largest contiguous low-cirrus field with good coverage is the SWIRE Lockman Hole field (hereafter SLH). We also reduce the First Look Survey (FLS) extragalactic field, the first released, for comparison. As can be seen in Table I, the SLH field is considerably lower in cirrus background (as known from IRAS and HI maps prior to observations) and larger.

The maps were made in scanning observation mode, with the MIPS arrays performing simple back-and-forth scans. At the end of each scan (except in a small fraction of the data), the pointing was stepped by (148"/276") in the cross-scan direction in the SLH/FLS surveys (nominally just under half the 160  $\mu$ m array width,  $\sim 9.25$  pix, for the SLH/ nominally 85% of the 160  $\mu$ m detector width,  $\sim 17.25$  pix for the FLS). All SLH scanning observation sequences, or AORs, were performed twice back-to-back. (The basic unit of planned observation activity with Spitzer is an AOR, or Astronomical Observing Request. Here we refer to the series of actions by the observatory, and the associated data, as the AOR for brevity.) A simple representation of the scan pattern is given in Fig. 1 for both maps.

### 2.2 Instrument Behavior - Challenges with Ge detectors

The MIPS camera 160  $\mu$ m measurements are made via a stressed Ge:Ga detector array. The response of these detectors is measured frequently using flashes ("stims") from a light source within the camera at a regular period during normal observations. Ge detectors are subject to random and 1/f noise components, including gain drift, and "memory" effects, which are extremely difficult to model and correct. (The so-called memory effects are dependences in responsivity of the detector on the history of flux the detector has been exposed to.) In practice, drift and memory effects are mostly, but not perfectly, corrected. In scanning or rapid chopping observations,

the rapid appearance and passing of the sources in a given detector pixel limits drift and memory effects to those associated with short time constants. The stims do a good job of tracking the detector response on short time scales, and the Spitzer Science Center (SSC) reduction does a good job of producing repeatable point source fluxes. The Pipeline reduction procedures are discussed in detail in Gordon et al. (2005; but note that the implementation of these procedures by the SSC may differ in small ways). The Spitzer Data Handbook states that MIPS 160  $\mu$ m fluxes are repeatable to about 4% with an absolute uncertainty of about 20%. However, these numbers do not apply to background fluxes; the instrument is not at all optimized for background observations where long time constant effects ("slow response behavior") can complicate the reduction and interpretation of the data. According to the Data Handbook, point source measurements should be made by subtracting the median background from each frame before analysis, i.e. the background information should be discarded. The Data Handbook also gives instructions for reducing observations of bright extended emission sources for Ge detectors; the instructions for reducing observations of faint extended structures are conspicuously absent. This underscores the point that MIPS is not optimized for background measurements. The SSC has not thoroughly investigated the properties of the instrument for low-flux very extended structures, the fluctuations in the sky background. Nonetheless, we shall demonstrate below that the problems associated with our data are manageable, and a great deal of information is available in these maps.

### 2.3 Map Reduction

Our co-added maps, which have pixels of the nominal camera pixel size, give the average of the flux measurements closest to each pixel center. No re-sampling of the maps and no distortion corrections have been applied at this time because we are interested in structures much larger than the camera pixel size.

#### 2.3.1 Data Selection

This work includes data from pipeline version 11, which includes previously embargoed data<sup>1</sup>. Some data covering our se-

<sup>1</sup> In our initial reductions and pre-publication versions of this paper, the data were processed by the SSC pipeline version 10. The version 11 data show improved quality.

**Table 2.** SLH Data and Zero Point Constants<sup>a</sup>

AOR Key	Offset
5177088	-0.0410045
5177344	0.0838553
5179136	-0.0582686
5179392	0.0984183
5179648	0.0494460
5179904	-0.0894248
5180160	0.0509532
5180416	-0.00977480
5180672	-0.0789033
5180928	0.0552630
5181184	0.0140596
5181440	-0.0669587
5184768	-0.0396491
5185024	-0.143126
6592512	0.00856844
6592768	-0.124137
6593536	0.0775429
6593792	-0.0734718
6594048	-0.0432453
6594304	0.00904450
6595072	0.0809884
6595328	-0.0681358
6596096	-0.0501895
6596352	-0.0108055
7770368 <sup>b</sup>	0.463996
7770624 <sup>b</sup>	0.331227
9628672	0.0402081
9628928	0.0327531
9629440	-0.0725303
9629952	0.0269623
9630208	-0.0331634
9630464	-0.0134986
9630720	-0.0330788
9630976	-0.000532301
9631744	0.0146916
9632000	-0.0804646
9633280	-0.0644805
9633536	0.0322532
9633792	-0.0983279
9634048	0.119130
9634304	-0.00922350
9634560	0.0412873
9634816	0.00126636
9635072	-0.0397363

<sup>a</sup> Variance with offsets: 239335. Variance without offsets: 244011.<sup>b</sup> These two AORs are from the validation scans, taken in a different epoch from the rest of the data, when the estimated zodiacal light contribution was 0.22 MJy/Sr lower.

lected fields was excluded from our analysis due to data quality or instrument settings. In the SLH maps, a rectangular patch of sky near  $(\alpha, \delta) = (163.5^\circ, 57.6^\circ)$  is covered in AORs 9632512 and 9832256. These data have high noise and so were not used in our map, leaving a small rectangular region without data, which we refer to as the “window”. These data sets clearly dominated our rms noise map, described below, with a median rms of 0.33 MJy/Sr in these regions vs. 0.23 MJy/Sr typical

of the rest of the map. (The noise had structure in the scan direction, and so is likely due to drift or memory effects; it is not random noise.) We also excluded data from PID81, which were taken with different instrument settings (including stim period) and were not appropriate to combine with the rest of our data. Table 2 gives a list of AORs which identify the data used. In the FLS map, all data were used.

### 2.3.2 Stim Correction

In both “raw” maps (direct co-adds of Basic Calibrated Data, or BCD), sharp parallel lines can be seen perpendicular to the scan pattern (See Fig. 2). These correspond to the frames taken just after the stim flash response measurements; the effect is referred to as a “stim-flash latent”. The stim flash itself necessarily contributes to memory effects in the detectors, as would any illumination. These effects depend on the integrated illumination history, not just the instantaneous brightness. Although the flash is very bright compared to typical source and background fluxes, it is very short in duration, producing small integrated fluence, and so causes only a small memory effect. Unfortunately, the small stim latent is significant compared to the faint CFIB.

Figure 3 shows BCD light curves from the observations of the SLH field at  $160 \mu\text{m}$  (AOR 5177344) folded at the stim period. Here, each period of data was divided by the median of the data during that period in order to remove variations of the sky level during the observation. In most pixels, the residual effect is 10% - 15 % in the time bin or DCE after the stim flash, much greater than the error bars from the variation in sky flux (3-5%; see Fig. 3). In the third and following pixels after the flash, however, the effect (0-3%) is rarely statistically significant. We applied a correction for this stim flash latent residual, simply the inverse of the folded and normalized timelines. A comparison of the sky maps made with and without the stim flash latent corrections, shown in Fig. 2, is dramatic. The dominant structure in the raw map, the lines made by the stim-flash latents, has been removed.

### 2.3.3 Illumination correction

The Spitzer Data Handbook recommends that an illumination correction be made for extended source observations. We therefore performed corrections similar to those for CCD flat correction. We found the median value for each detector over a large set of data; this median “image” was then normalized, and all data in the sample were then divided by the median image. We tested making a different illumination correction for each scan (i.e. correcting only the data between each change of scan direction, as recommended in the Data Handbook), and also using the same correction for an entire AOR. If an illumination correction were beneficial, we would expect that the rms deviation between repeated measurements of the same sky would decrease. In both cases, no significant decrease in rms deviation was achieved.

### 2.3.4 Zero-Point Errors

In our initial co-added maps, regions associated with a given AOR appeared to have discontinuous flux on the borders of regions covered by other AORs. On further investigation, we found that this was reflected in a systematic discrepancy between measurements of the same sky position during different AORs. This can easily be seen in the histogram of median AOR data-map deviation. (We define the deviation  $\delta_i$  of each measurement  $f_i$  in a given AOR at a sky location  $\mathbf{r}(i)$  to be the difference between that measurement and the map at the location of the measurement, or  $\delta_i = f_i(\mathbf{r}(i)) - \text{map}(\mathbf{r}(i))$ . The map value is just the average of all flux measurements  $f$  at any given position,  $\text{map}(\mathbf{r}(i)) = \langle f(\mathbf{r}(i)) \rangle$ . The median deviation for a given AOR is then  $D = \text{median}(\delta_i)$  for all  $i$  in the AOR.) The histogram of median AOR deviation is shown in Fig. 4 for our selected data. The obvious outliers in the SLH data are from observations of the “validation region” of the survey. The validation region data were taken 2003 December 9, long before the rest of the survey, 2004 May 4-9. According to the SSC tool SPOT, the level of zodiacal light is estimated to be 0.22 MJy/Sr lower during the validation observations. However, the deviation in the other data sets taken at the same time is apparently instrumental in nature.

We used numerical techniques to find the minimum variance (of repeated observations of the same sky pixel) set of additive zero point constants to reduce this problem. The set of minimum variance constants is given in Table 2 for our SLH map.

### 2.3.5 Zodiacal Light

No zodiacal light correction was applied (except in the correction for a different observation epoch, as described above); we show in Section 3, Map Power Spectra, that this produces negligible effects on our results.

### 2.3.6 Full Maps

The full SLH map with all the corrections described thus far is shown in Fig. 5. The FLS map is shown in Fig. 6.

### 2.3.7 Striping

The maps have structure which clearly follows the scan pattern; such structure is referred to as “stripes”. This can be seen easily on a computer screen, though it often shows up poorly in printed reproductions. The scans are all approximately parallel in the maps (except for small validation regions), enhancing this structure. In Fig. 7 we show the SLH map smoothed at a size of 1/2 the instrument width to show this effect more clearly; the figure has been rotated so the scans are vertical, and the structure is also vertical. The structure in the map looks like large blocks, the regions covered by each AOR, rather than thin stripes.

Monotonic drift in most detectors in the array, zero-point offsets in most detectors, and memory effects can contribute to stripes. We compared the individual detector timelines to the average of all measurements at the same map points, and determined that there was no significant monotonic drift in most pixels. However, we showed above that a median deviation with the same characteristics as a residual zero-point offset is

present in the data. This would cause structure at AOR boundaries, as is observed. Detector memory effects are extremely difficult to test for, however, and the contribution of this effect remains unknown. Detector memory effects can cause bright extended emission regions to appear “smeared” across the map in the scan direction, resembling stripes. When the instrument finishes scanning a region and points to a new one, the detector is usually annealed, and its flux history is “reset”. The background in the new region will reflect the detector’s new history while in that region, which will be different than in surrounding regions; hence the discontinuities at the boundaries of the regions covered in each AOR could be caused by memory effects. There is one region where significantly less striping occurs in the SLH map, in the validation region (see Fig. 5 and Fig. 7), where some scans were done at large angles to others. (Such scans are said to be “cross-linking”, described below.) The worst striping is at the extreme right edge of the map in Fig. 5 and Fig. 7, where several of the brightest, more extended emission regions are located. This region was not included in our power spectrum analysis below.

## 3. Power Spectrum Analysis

### 3.1 Power Spectrum Calculations

Our analysis closely follows that of Lagache et al. (2000). The basic steps for analysis of the CFIB are: (1) A power spectrum is made from the map. (2) Noise is subtracted from the power spectrum, and it is corrected for instrumental response. (3) The local foregrounds are then subtracted to yield the power spectrum of the CFIB. This section will cover all steps of this analysis, and the results will be covered in the following section.

We analyze structure using a simple two-dimensional discrete Fourier Transform on square map sub-sections (shown in Fig. 5 for the SLH map). We report only the average magnitude squared of the Fourier components  $P(k)$  in binned  $k$  intervals ( $k = (k_x^2 + k_y^2)^{1/2}$ ). We did not apodize our maps prior to power spectrum analysis in order to preserve the information in the corners.

In order to measure the noise power spectrum, two separate maps were made from the alternating (i.e. even and odd) measurements at each sky location. The even and odd maps were then subtracted to make a difference map which was analyzed to determine the noise power spectrum.

### 3.2 Map Preparations

#### 3.2.1 Missing Data

Certain artifacts of the maps had to be “repaired” before proceeding to power spectrum analysis. Our SLH field map contains an approximately rectangular section, the “window”,  $0.29^\circ \times 0.63^\circ$  ( $66 \times 143$  pixels) for which all AORs have excessively high noise (see section 2.3.1). Because the region includes only a small fraction of the map area ( $0.18 \text{ deg}^2$ , 2.1% of our square map size), the loss of these data should have only a negligible effect on our results. We compared several methods for replacement of the data in this region: replacement with contiguous sections of data taken “above” and “below” the window, from both “sides” of the window, and finally we replaced

the data with a smooth fifth order polynomial fit to the data around the window. The power spectrum results were insensitive to the choice of replacement method (or interpolation order), and we finally adopted the smooth fit.

There are unobserved pixels in the maps; in the FLS about 1.3 %, in the SLH  $3 \times 10^{-4}$  of the area in our square map was unobserved (in addition to the missing rectangle). We replaced all small groups of unobserved pixels with a local median of non-zero pixel values with a center-to-center distance of  $\leq 10$  pixel widths. These replacements had minimal effect on the final power spectrum.

### 3.2.2 Source Removal

We removed sources from our maps before calculating power spectra using the SEXTRACTOR program (Bertin & Arnouts 1996) to find source locations (x,y) and x and y sizes ( $s_x, s_y$ ). Sources with isophotes more than  $1.5 \sigma$  (0.53 MJy/Sr) above the local background were removed, if they had more than four or more adjacent pixels above the threshold. At the location of each source centroid, a circular region within diameter  $d_{replace}$  was replaced with local background values. The resulting one-dimensional source sizes  $s = \text{maximum}(s_x, s_y)$ , yielded good results in the range of about 5.65 to 9.5 pix. For  $s < 5.65$  pix we used  $d_{replace} = 5.65$  pix. For  $5.65 \text{ pix} < s < 9.5$  pix we used  $d_{replace} = s$ . For  $s > 9.5$  pix we used a log truncation,  $d_{replace} = 9.5 + 1.5 \ln(s/2-3.75)$ , then we truncated that result to enforce a maximum of 14 pix.

For each pixel in the replacement region, the median of an annulus of inner and outer diameters  $3 d_{replace}$  and  $4 d_{replace}$  replaced the pixel value. In the end, the power spectra were extremely insensitive to the widest possible range of  $d_{replace}$ , detection threshold, etc., except at the highest frequencies, which have no effect on our conclusions.

### 3.2.3 Sub-Sample

Because our power spectrum analysis software only accepts square maps, and because we wished to analyze the largest possible contiguous areas we analyzed the square sub-samples of each map indicated in Figs. 5 and 6. We excluded a region of the far right edge in Fig. 5 from our SLH map because of high cirrus and probable memory effects. The SLH sub-sample area is  $8.47 \text{ deg}^2$ .

### 3.3 Features of the Raw Power Spectrum

The power spectra of the SLH and FLS maps are shown in Fig. 8 and Fig. 9. The following features are of interest: The lowest frequency bins look like a simple power law; in this region IR cirrus emission is known to dominate. In the mid-frequencies, there is excess emission above this power law. This is the signal due to cosmological sources. At the high frequency end, the signal is strongly modulated by the instrumental response function, the power spectrum of the point spread function (PSF) of the instrument and telescope. The power spectrum of the PSF provided by the SSC (simulated by the STINYTIM routine) is shown in Fig. 10. At the highest frequencies, the signal becomes dominated by noise; noise power is within a factor of two of signal by  $k > 0.7 \text{ arc min}^{-1}$  for the SLH.

## 3.4 Systematic Effects

### 3.4.1 Zodiacal Light

The zodiacal light contribution at  $160 \mu\text{m}$  is small compared to other wavelengths, and so we did not remove zodiacal light from our maps prior to analysis. At  $160 \mu\text{m}$ , a simple smoothed planar fit to the zodiacal background values predicted by SPOT was analyzed to determine the effect on the power spectrum. We estimate that zodiacal light contributes less than 2.5% of the spectral power in any bin, with a maximum contribution at low  $k$ .

### 3.4.2 Structure Due to Zero-Point Offsets

As shown in section 2.3.4, there are systematic deviations in each AOR data set that have the character of a zero-point offset. Such a set of zero-point offsets might cause false structure because the scan pattern is rather regular. We tested the effects of such offsets on the power spectrum by producing a known, “synthetic sky”, then simulating observation of this “synthetic sky”, including the addition of noise and offsets. Comparison of the known input synthetic sky and the resulting maps will then give the systematic effects due to the zero-point offsets.

We produced the synthetic sky with a very simple CFIB + single-component foreground cirrus model. We used actual cirrus images from ISSA plates re-binned to the same pixel dimensions as in our map. This cirrus foreground has the desired -3 slope spectrum. We added a Poisson distributed synthetic CFIB signal (i.e. with a flat power spectrum), then scaled the two components to the power measured in our SLH map for the cirrus and CFIB, respectively. We then simulated scanning observations, using the same scanning pattern as in the SLH observations.

**Offset Correction Simulation Test:** In our first test, we essentially measure the ability of our mapmaking software to correct for offsets given the SLH scan pattern and measured noise. We started with our synthetic sky simulation and added the same noise power as observed in the SLH, and *the same set of deviations measured in the actual BCD data*. We made different realizations of our simulated maps, adding the measured deviations from the SLH data to the simulated data sets, but assigning them to the different AOR data sets in a different, random order in each realization. (We used different realizations in order to understand effects similar to offsets in a very general way.) We reduced these simulations in the same way as our real maps, fitting for zero-point offset corrections. At this point, most of the effects of offsets should have been corrected, and we expect little effect on the power spectrum.

The simulations showed only a very small effect on the power spectrum ( $< 15\%$  for  $k < 1 \text{ arc min}^{-1}$ ), negligible compared to the uncertainty due to the fit errors at low  $k$ . The software succeeded in fitting good offset corrections. The behavior was consistent among all our simulations.

**Residual Deviation Simulation Test:** In this test we observe the effects of *uncorrected* offsets on the power spectrum, to match those seen in Fig. 4b. Starting again from synthetic sky maps, we added the same random noise power as observed

in the SLH, and *the same set of residual deviations measured in our actual final SLH map* (see Fig. 4b). We made different realizations of our simulated maps, adding the same measured residual deviations, but assigning them to the different AOR data sets in a different, random order in each realization. (We used different realizations in order to understand effects similar to the measured residual deviations in a very general way.) We reduced these simulations in the same way as our real maps, but *without* correcting these offsets. This had a larger effect on the power spectrum, ( $< 25\%$  for  $k < 1 \text{ arc min}^{-1}$ ; See Fig. 11), but still very small compared to the fit errors. Below, we use this function to make a correction for this effect, the inverse of the function shown in Fig. 11.

### 3.5 CFIB Analysis

The CFIB analysis requires correction of the raw map power spectrum for instrumental effects and removal of foregrounds.

#### 3.5.1 Instrumental Response Function

The sky map may be described as the convolution of the real sky and an instrumental response function plus noise. The power spectrum of the sky may therefore be derived from the instrumental power spectrum minus the noise power spectrum, divided by the response function of the instrument. In Lagache & Puget (2000) and Miville-Deschenes, Lagache, and Puget (2002), the instrumental function was derived from the power spectra of cirrus-dominated maps by assuming that the (cirrus-dominated) sky power spectrum was dominated by a  $-3$  slope power law. Large Spitzer maps of such regions are not readily available. In the analysis below, we assume that the PSF dominates the instrumental response function, and approximate our instrumental response function by the power spectrum of the PSF given in Fig. 10.

Since we are looking for departures from the smooth cirrus power law in our power spectra, assuming a smooth response function without justification could lead to the misidentification of instrumental features as features of the sky. In order to address this problem, we used the limited cirrus observations available. The FLS galactic observations do include a  $15' \times 1^\circ$  strip observation of cirrus, AOR 4962304. To reach scales large enough to be of interest, we analyzed one-dimensional strips in the long direction of this map, reduced in the same way as our extragalactic field maps. The cirrus map spectrum (Fig. ??) shows a smooth power-law like function at the lowest map frequencies, and noise and artifacts dominate at high frequencies. Assuming that the cirrus is a perfect power law, and assuming this map is the convolution of this power law and the instrument function + noise + artifacts (at high-frequency), we can draw an important conclusion from these data: from  $0.1$  to almost  $0.01 \text{ arc min}^{-1}$  the instrumental function must be smooth, with bumps or wiggles  $\ll$  factors of two.

#### 3.5.2 Residual Offset Corrections to the Power Spectrum

We also applied a correction for our residual offsets (measured residual deviations) described in Section 3.4.2. To correct for these residual offsets, we divided out the effect of these offsets in our simulations, the function given in Fig. 11.

#### 3.5.3 Foreground Cirrus Subtraction

Previous measurements of the sky on scales from arc seconds to much larger than our maps have shown that cirrus structure has a power law shape with a log slope very close to  $-3$  (e.g., Wright 1998, Herbstmeier et al. 1998, Gautier et al. 1992, Kogut et al. 1996, Abergel et al. 1999, Falgarone et al. 1998). This very steep slope means that this structure must dominate at the lowest frequencies (as shown in Fig. 8). Following Lagache & Puget (2000), we subtract a power law fit of the low-frequency structure from our power spectrum in order to remove the cirrus contribution. We fit a power law function to the lowest four bins of  $k$  in order to get a good fit of the cirrus structure in the range of  $k$  where it dominates. Given the extensive evidence for power law cirrus structure, we decided to empirically determine our fit errors from the deviation in the log of our data from the even-weighted power law fit. The fit errors dominate the uncertainty in our CFIB measurements at low- $k$ . The CFIB fluctuation power spectrum is shown for the SLH field in Fig. 13.

## 4. Results

### 4.1 The CFIB Fluctuations Measurement

#### 4.1.1 The SLH Fluctuation Spectrum

The observed CFIB power spectrum is described in gross terms as showing high power at low  $k$ , decaying rapidly to  $\sim 0.1 \text{ arc min}^{-1}$ , with a relatively flat region  $\sim 0.15 - 0.4 \text{ arc min}^{-1}$ . If the sources of the CFIB were distributed at random in space, a flat power spectrum would be expected. What is observed is clearly different. This excess CFIB power at low  $k$  has been identified as the signature of clustering of CFIB sources, discussed in the following section. The error bars on the lowest few  $k$  values are large due to the finite uncertainty in the subtracted power law fit. However, the remaining points have quite reasonable uncertainties, and we concentrate on these in our discussion. At the large  $k$  values, the noise becomes significant and the instrumental correction becomes very large (see Fig. 8; the figure is cut off at  $k = 1.0 \text{ arc min}^{-1}$ .)

#### 4.1.2 Comparison with Predictions

In Lagache, Dole & Puget (2003), a pre-Spitzer simulation of the FIR sky was described (and made publicly available). The simulation used a relatively simple model galaxy distribution (“normal” spirals + starburst galaxies) and evolution constructed to be consistent with IR - mm source counts available at that time, with sources distributed at random and interstellar foreground cirrus. Perrotta et al. (2003) showed the effects of

**Table 3.** Low- $k$  Power Law Slopes

Map and Sample	Cirrus Power Law Slope <sup>a</sup>
SLH,corrected	$-3.13 \pm 0.28$
SLH,uncorrected	$-3.10 \pm 0.25$
FLS	$-3.12 \pm 0.55$

<sup>a</sup> Power law fit to the first four points of the power spectrum.

predicted clustering on background power spectra. This theoretical prediction is shown superimposed on the power spectrum of the Lagache, Dole & Puget (2003) simulation in Fig. 14. The gross features of the prediction agree with our CFIB spectrum, in that there is a substantial low- $k$  excess above a relatively flat region in the mid- $k$ , the clustering “signature”, clearly inconsistent with a Poisson distribution of sources.

In detail, however, Perrotta et al. (2003) predicts that the power spectrum excess is almost flat for  $k$  in the range of 0.01 to 0.1 arc min<sup>-1</sup>, which is not consistent with our observations. Our points with small error bars near  $k = 0.045$  and 0.06 arc min<sup>-1</sup> require a drop of greater than a factor of 3 in power between these bins and 0.1 arc min<sup>-1</sup>. The Perrotta et al. (2003) prediction is dominated by contributions from starburst galaxies, which are flat at  $k < 0.1$  arc min<sup>-1</sup>. Spirals, contrarily, have a spectrum that falls steeply with  $k$ , precisely what is required to reproduce our sharply falling spectrum. Our results suggest that the contribution of spirals in the Perrotta et al. (2003) model is then underestimated by more than a factor of 10 (estimated by scaling the relative contributions of the two source types given in Fig. 7 of Perrotta et al., 2003). It is beyond the scope of this work to examine all the details of Perrotta et al. (2003) modeling and assumptions, however, the power is dependent on the estimated bias of each source type, as well as their relative evolution.

#### 4.1.3 Likely Systematics

These results are from a relatively simple analysis which relies on the assumption that the SSC PSF simulation gives the correct instrumental response function. However, it is unlikely that an instrumental feature would produce our excess low- $k$  (large-scale) power. Large and medium scale power in the instrumental response function can only come from changes in the instrument over times comparable to observation of the whole map; the camera PSF has no structure on large scales. The map was sampled rather uniformly on the large scales, with essentially the same scanning overlap, redundancy, scan speed, etc. across the map. The FLS cirrus strip power spectrum was quite smooth, showing that there can be no bumps in the instrumental response in this frequency range. The ISO instrument (Lagache & Puget 2000) also had no features in the instrumental response in this frequency range, and in general, such features would not be expected. We note that the excess clearly extends into the mid- $k$  region (the power is more than a factor of two above the flat region all the way up to  $k = 0.08$  arc min<sup>-1</sup>). The map contains many samples of the associated size for mid- $k$  values, therefore the measured behavior can-

not be a statistical anomaly. We also note that spurious artifacts generally occur at much smaller spatial scales.

In section 3.4.2 we addressed the possibility that systematics with the character of an instrumental zero-point offset could cause erroneous structure in our power spectra. The result of our simulations showed that there was a small effect, and we corrected for this. The consistency of our simulations makes us confident in this correction. In the end, however, the erroneous structure had little effect on the results, producing almost no effect on the cirrus fit. Table 3 lists the power law fits to the SLH power spectrum with and without corrections, and they are essentially indistinguishable. Because the dominant error in the CFIB spectrum is the power law subtraction uncertainty at the mid- $k$  points of interest, and because the power law fit did not change, the correction yielded no significant change in the results. In all our offset simulations, effects on the power spectrum were small and had no significant effect on our results; our results are therefore robust against such systematic effects, within our errors.

#### 4.1.4 Dispersion in the SLH Results

The SLH sub-sample was selected *a posteriori*, avoiding bright cirrus regions and map edges. Reducing a few different sub-sample regions yielded some larger uncertainties in the power law fits, with larger errors as the subsample region moves closer to the bright region at the right edge of the map. All power spectra are consistent, however.

We note that the two SLH validation AORs yielded the largest deviation even after zero-point correction (Fig. 4). Removal of these two AORs from the map yielded results consistent with those reported above. Because we did not find obviously anomalous behavior in the region covered by these data in the difference maps, however, we judged that elimination of these data may not be justified, therefore we did not eliminate these data.

#### 4.1.5 First Look Survey Results

The FLS field power spectrum has no evident turn-off from the cirrus power law until about 0.09 arc min<sup>-1</sup>, whereas in the SLH power spectrum, the turnoff was at  $\sim 0.03$  arc min<sup>-1</sup>. The difference is likely due to the greater strength of the cirrus emission in the FLS field. The cirrus power is more than 10 times higher in the FLS at 10<sup>-2</sup> arc min<sup>-1</sup> than in the SLH. The power law fit was again made from the first four bins. However, the field is smaller, so the first four bins are at higher frequency than in the SLH. In this field, the power law fit has larger uncertainty than in the SLH. Because of this larger uncertainty, the signal in the low to mid- $k$  range of interest has large error bars, and the resulting CFIB measurement is not interesting. This result is not unexpected, however: the combination of strong cirrus in the field (requiring very small fit error for CFIB measurement), and sampling the cirrus at a higher  $k$  (because the field is smaller) where the CFIB can interfere makes for an *a priori* difficult measurement.

#### 4.2 Comparison to Previous Results

The SSC provides a tool to separately predict the local, ISM, and extragalactic background components (part of the SPOT software) incorporating HI data and IR measurements (essen-

tially the Schlegel, Finkbinder & Davis (1998) Results), and knowledge of the MIPS instrument. Table 1 shows that in the SLH, the median total background is more than 18% off the prediction. Since the predictions of SPOT agree very well with other measurements in this wavelength regime (e.g. ISO measurements in the FIRBACK fields; Lagache & Dole 2001), this suggests that some modification of the MIPS calibration is in order. The MIPS 160  $\mu\text{m}$  camera has a known, significant optical light leak. The MIPS calibration, now based on asteroids, might cause a significant error without correction for optical background flux.

Lagache & Puget (2000) fluctuation spectrum results are plotted along with our results (the diamond symbols) in Fig. ?? (The values were taken directly from their Fig. 3.) The overall agreement is very good, given the bin-to-bin scatter, differences in instruments, and realistic measurement and calibration uncertainties.

Lagache & Puget (2000) reported CFIB spectrum results consistent with a constant level. However, the Lagache measurements apparently reflect the same increase in power toward low frequency as observed here, at all except their very lowest frequency point. (For  $k > 0.5 \text{ arc min}^{-1}$  the correction for the PSF becomes large for both measurements, and may not be reliable.)

### 5. Possibilities for Future Improvements

At this time, the problems in the map are dominated by scan-pattern related structure. In terms of data reduction, various frequency space filtering methods for removing stripes seem promising, and have been demonstrated on other types of maps (see, e.g., Miville-Deschênes & Lagache 2005). In addition, various algorithms are available for optimum statistical weighting of map data. We found, however, that unless the striping in the maps are significantly reduced, these algorithms do not produce good results.

We find that the greatest potential for improving these measurements is in acquiring new data on the SLH field in a manner appropriate for background observations. The MIPS observations are truly exceptional compared to typical background observations in the degree to which “cross-linking” scans were *avoided*. Virtually all cosmic microwave/mm background experiments incorporate cross-linking in their scanning strategy. Such a strategy causes each sky pixel to be re-sampled along significantly different scanning paths on the sky. A simplified example of cross-linking scans would be a series of two rectilinear raster maps of a region oriented at  $90^\circ$  to each other. Two sky positions measured along the same scan across the first map would be measured on different scans in the second map. Comparison of repeated observations on the same and different scans allows identification and measurement of any systematics that affect the measurements differently on the same and different scans. In the general case, this technique allows inter-comparison of measurements made close together in time (i.e. on the same scan) with those made at much longer time scales. In our case, this comparison would clearly identify and measure the zero-point offsets. In all of the large MIPS surveys,

rectangular regions of the sky were observed during each AOR, and then immediately repeated on almost precisely the same path (with only minor exceptions). The rectangular regions were oriented very nearly parallel, no scans were made along significantly different directions (except in the very limited verification observations), and these regions had only small edge overlap. Cross-linking was essentially *minimized* in the existing surveys, permitting intercomparison among only a small fraction of data measured on different paths in different AORs. It seems clear that if cross-linking MIPS scans were added to existing Spitzer survey regions, significant improvement in the background fluctuation measurement would result.

## Conclusions

In this paper we presented co-added maps from two large Spitzer survey fields observed with the 160  $\mu\text{m}$  MIPS array. Instrumental artifacts, and artifacts related to the scan pattern were observed, but these effects were substantially reduced by a variety of corrections. We measured a cirrus power law slope of  $-3.13 \pm 0.28$  in the Lockman Hole field. Subtracting this power law yielded a CFIB spectrum dropping rapidly from  $k \sim 0.03 \text{ arc min}^{-1}$ , to  $k = 0.1 - 0.2 \text{ arc min}^{-1}$ , and a flatter region at higher  $k$ . Any assumption of a power law cirrus contribution plus a flat power spectrum from the ensemble of sources, i.e. from a random distribution of sources, is not consistent with our observations. The gross details of our results are consistent with predictions of a clustering “signature” in the CFIB power spectrum.

## Figure Captions

Fig. 1 Scan Patterns. A simple representation of the scan pattern, a line connecting each pointing of the camera sequentially, is given above for both fields. Part a) shows the scan pattern for the FLS Extragalactic Field. Note that all scan paths are close to parallel, even those in the verification region (repeated observations denoted by denser region at center). Part b) shows the Lockman Hole (SLH) Scan Pattern. Note that all scan paths are close to parallel except for those in the validation region (repeated observations denoted by dense region of paths at approximately 45 degrees to nearby paths, at upper middle of figure).

Fig. 2 Stim Latent Correction. The two figures show a small sub-section of the co-added SLH map. The uncorrected subsection, top, has regular, bright horizontal bands, perpendicular to the scan direction, which dominate the structure. These are due to the stim latent effect. The latent bands are completely removed by the correction process, shown in the lower figure. The intensity scale (MJy/Sr) is given at the right side of the figure; the spatial scale markings on the bottom and left sides of the figure are in units of instrumental pixel widths. The data are from the SWIRE Lockman Hole observations; but all data we examined have essentially the same effect.

Fig. 3 Stim Latents. The data from three different detector pixels are shown folded at the stimulator flash period. To show possible time-dependence of the phenomenon, the first 1/3 of



the data were represented by a cross, the second third by a diamond, and the final third by a filled circle. The time bin after the stim flash (which occurs in bin 0 in the figure) is almost always high in almost all channels. (These data are from AOR 5177344.)

Fig. 4 Median AOR Deviation. In part a), above, the histogram of median deviation (median of data-map) for each AOR in the SLH map is shown. The two outliers are 770624 and 770368, the validation region scans (-0.34, -0.48). In part b), below, on the same horizontal scale, the histogram of residual median deviations is given (i.e. *after* the optimal set of offsets was added to the data). The added offsets make the distribution much more narrow. The two outlying points are again AORs 770624 and 770368 (-0.08, -0.11).

Fig. 5 Full SWIRE Lockman Hole (SLH) Map. The full SLH 160 $\mu$ m Map is shown above. The small protrusions at the upper right are the edges of the validation region scans, which are roughly 45° from the main scans. The white rectangle indicates the square sub-region used in our analysis. Regions further to the right are not analyzed here due to the strong cirrus emission in this region. The unnaturally smooth rectangle centered near 250, 425 is the “window” referred to in the text with interpolated data (see text section 3.1). The x and y spatial scales are in pix (15.9”/pix). The bar at right indicates an intensity scale, in MJy/Sr. The image is rotated so that the main scans are approximately vertical.

Fig. 6 FLS Map. The full FLS map is shown in the picture above. The white rectangle indicates the square sub-section analyzed in this paper. The verification region, where additional observations were made, is a small region just below center. The same spatial and intensity units are used as in the previous figure. The figure is rotated so that the scans are approximately horizontal.

Fig. 7 Lockman Hole Map Smoothed by 1/2 Detector Width. This image of the map has been smoothed to better demonstrate the presence of large-scale structure in the scan direction. Structure that looks “smeared” in the scan (approximately vertical) direction is associated with the more extended and bright emission on the map, and therefore could be due to memory effects. Note that in the validation region there is significantly less “smearing” than in the rest of the map due to sampling in different scan directions, i.e. cross-linking. The same spatial and intensity units are used as in the previous figure.

Fig. 8 Power Spectrum of Lockman Hole Map. Sources were removed from our square subsample of the SLH map for this power spectrum. Filled circles indicate measured  $P(k)$ , open circles indicate power corrected for instrumental response and residual zero-point effects. The power law fit is shown as a dashed line in the range of measurements where the fit is made, and its extrapolation is denoted by a dotted line. The continuous line at the bottom of the figure gives the measured noise spectrum. See text for additional details.

Fig. 9 FLS Map Power Spectrum. The FLS power spectrum is shown in the figure above with the same symbols as in the previous figure. Note that the much larger SLH field had measurements down to smaller  $k$  (Figure 8). The power law extrapolation is not much higher than the data up to 0.08 arc min<sup>-1</sup>,

and so the CFIB cannot be measured easily or accurately at low frequency in this field.

Fig. 10 The Power Spectrum of PSF, generated by the routine *Stiny Tim*, is shown in the figure above.

Fig. 11 Effect of Residual Offsets on the Power Spectrum. The figure shows the relative effect of the observed residual offsets on the power spectrum. See Section 3.4.2 for details.

Fig. 12 Cirrus Map Power Spectrum. The figure shows the average of 8 power spectra each made from one dimensional slices of the FLS cirrus strip-map. Each strip was the average of 5 contiguous lines of pixels along the long axis of the map. The low frequencies show a close fit to a power law, with deviations less than a factor of two. Significant deviations would be expected simply due to the small sample size. The close fit to a power law shows that the instrumental function must be smooth at  $k < 0.1$  arc min<sup>-1</sup>.

Fig. 13 CFIB Spectrum from the SLH (Lockman Hole) Map. The figure shows our noise-subtracted, instrumental response, and residual deviation-corrected CFIB spectrum of the SLH subsample (filled circles). The low-frequency power appears to fall rapidly to  $\sim 0.1$  arc min<sup>-1</sup>; there is a comparatively flat region  $\sim 0.15 - 0.4$  arc min<sup>-1</sup>. At the high frequencies (where power drops rapidly) instrumental response corrections become large. The error bars give the uncertainty in the cirrus power law subtraction and residual deviation correction only. The cirrus subtraction uncertainty dominates at low frequencies. The diamonds reproduce the results given in Lagache & Puget (2000).

Fig. 14 Simulation and Clustering Prediction. The power spectrum from the Dole et al. (2003) simulation (filled circles) shows a relatively flat Poisson component from  $k > 0.05$  arc min<sup>-1</sup>, whereas the Perrotta et al. (2003) simulation (dashed line), which includes clustering, shows a significant decrease in power all the way out to  $k > 0.2$  arc min<sup>-1</sup>.

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